MAGNETIC ACTUATION AND MOS-TRANSISTOR SENSING FOR CMOS-INTEGRATED RESONATORS

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ABSTRACT

We present a magnetic actuation scheme combined with a piezoresistive MOS-transistor sensing technique for CMOS-integrated resonators. It was developed for a cantilever resonator with on-chip amplifier, but is broadly applicable. The high efficiency of electromagnetic actuation significantly reduces the required operation power and allows for the use in portable devices. By use of stress-sensitive PMOS-transistors as active loads, the size of the piezoresistive Wheatstone bridge is significantly reduced. Thirdly, the post-processing sequence of the cantilever resonator has been optimized, so that only one photolithography step is necessary to release the whole mechanical structure. This facilitates the fabrication, increases yield and, thus, reduces fabrication cost.

INTRODUCTION

Micromachined resonant cantilevers constitute a highly sensitive type of mass-sensitive transducer with sub-picogram mass resolution in air. In resonant operation, the cantilever is excited harmonically and the change of the resonance frequency due to a small mass added on the cantilever is measured. In previous designs [1], the cantilever was excited thermally to harmonic vibrations using a heating resistor and the thermal bimorph effect between silicon and the dielectric layers on top. This excitation scheme typically needs 5 mW power consumption and leads to a static temperature increase on the cantilever. This degrades the sensitivity of the cantilever as a chemical sensor. The above disadvantages can be overcome by the use of magnetic actuation to excite the resonator [2]. Furthermore, the excitation frequencies can be extended to several MHz, far above the efficiency limit for thermal excitation. The price to pay is a more complex packaging process, since a permanent magnet needs to be integrated.

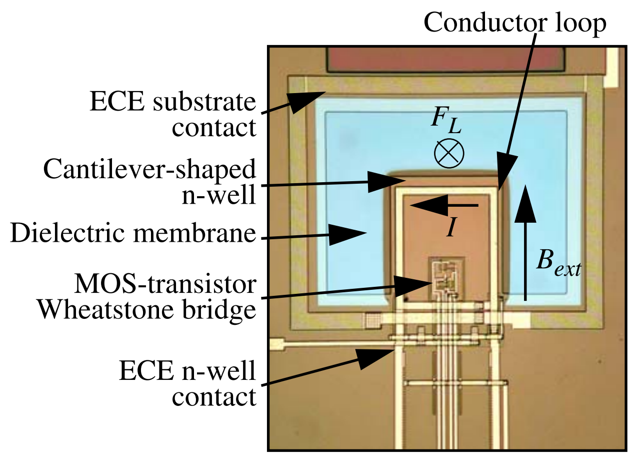

Figure 1: Micrograph of an electromagnetically excited resonant cantilever with stress-sensitive MOS-transistor Wheatstone bridge. Cantilever length is 150 µm.

MAGNETIC ACTUATION

Numerous experiments have demonstrated that micromachined structures can be excited by placing them in a permanent magnetic field [3,4]. Fig. 1 shows a photograph of the investigated cantilever resonator. It consists of the silicon n-well diffusion covered by dielectric layers provided by the employed CMOS process. For electromagnetic excitation, a current path in form of two loops made from the two metallization layers of the CMOS process is integrated onto the cantilever. The cantilever is placed in a transverse magnetic field B while a sinusoidal current I is applied to the conductor on the cantilever. At the free end of the cantilever the current and the magnetic field are oriented perpendicular to each other generating a Lorentz force F_L. The generated force is directed out of the cantilever plane and causes transverse vibrations of the canti-

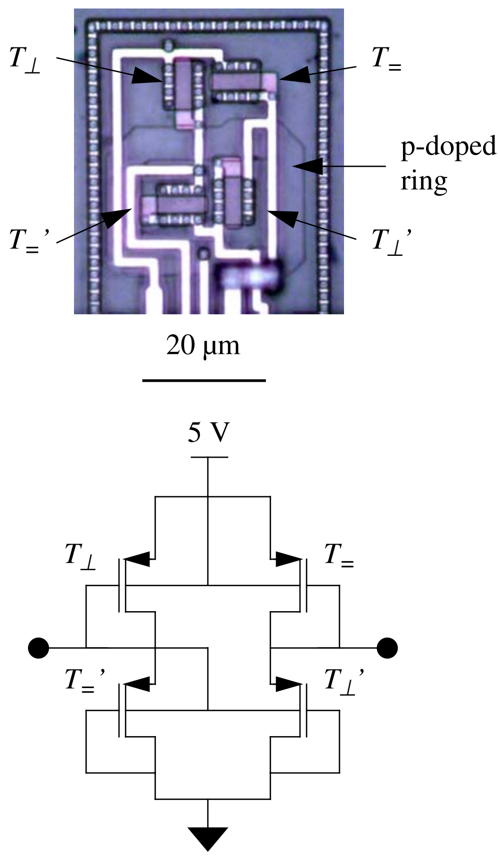

Figure 2: Photograph and circuit diagram of the stress-sensing PMOS transistors in a Wheatstone bridge configuration.

lever. A piezoresistive Wheatstone bridge formed by PMOS-transistors is integrated on the cantilever to detect these vibrations. The signals from the Wheatstone bridge are amplified by an on-chip low-noise fully differential difference amplifier with a gain of 30 dB and a corner frequency of 500 kHz.

TRANSISTOR-BASED DEFLECTION SENSOR

Diode-connected PMOS-transistors are used to sense the mechanical stress created by the cantilever vibrations. The effects of mechanical stress on transistor behavior have been studied for some time because stress can be induced by e.g. a variety of packaging processes. When used as stress-sensors, MOS-transistors offer the advantage of smaller size in comparison to diffused resistors, which allows further miniaturization of the cantilever, and direct integration into active circuitry [5]. As is the case for resistors, the basis for the piezoresistive effect in MOSFETs are changes in electron and hole mobility under the influence of mechanical stress. For enhanced sensitivity four PMOS-transistors were arranged in a Wheatstone bridge configuration. A close-up of the Wheatstone bridge and the circuit diagram are shown in Fig. 2. The Wheatstone bridge is biased at 5 V. The active loads have a resistance of 20 kΩ in order to minimize power dissipation. To ensure a small offset voltage at the Wheatstone bridge output the four transistors should match and show the same body effect. For this purpose, the bulk-source voltage needs to be zero. For the transistors $T_\perp$ and $T_=$ this is obtained by connecting the sources to the potential of the n-well forming the cantilever. Furthermore, to satisfy this condition also for the transistors $T_\perp'$ and $T_='$, they are placed in a separate n-well and connected to their corresponding output of the Wheatstone bridge. The n-well is isolated from the n-well forming the cantilever by a small ring of p-doped substrate. The size of this ring was chosen small enough, so that during the anisotropic etching the electrochemical etch stop still functions over the whole cantilever area.

The sensitivity of the PMOS-Wheatstone bridge is derived from a small-signal analysis. The amplified output signal of the MOS transistor Wheatstone bridge is:

$$U_{PMOS} \approx \frac{(U_B/2 - V_T)V}{2}(\pi_L - \pi_T)\sigma_\perp$$

with U_B being the dc biasing voltage of the Wheatstone bridge and V the amplification of the preamplifier. The piezoresistive coefficients for current direction along and perpendicular to the clamped edge of the cantilever are π_L and π_T, respectively. V_T is the threshold voltage of the PMOS-transistors, typically 0.9 V. The sensitivity is slightly smaller than for piezoresistors due to the effect of the threshold voltage and the higher small-signal resistance of transistors due to the involved feedback via the gate.

OPTIMIZED POST-PROCESSING

The cantilever resonator has been fabricated using a 0.8 µm CMOS process of Austria Mikro Systeme International AG, Austria, and two subsequent wet etching steps; anisotropic etching of silicon with KOH and wet etching of dielectric layers. Compared to the prior design, the fabrication process has been simplified, and only one photolithography step during post-processing to define the membrane and the cantilever geometry has to be performed. The

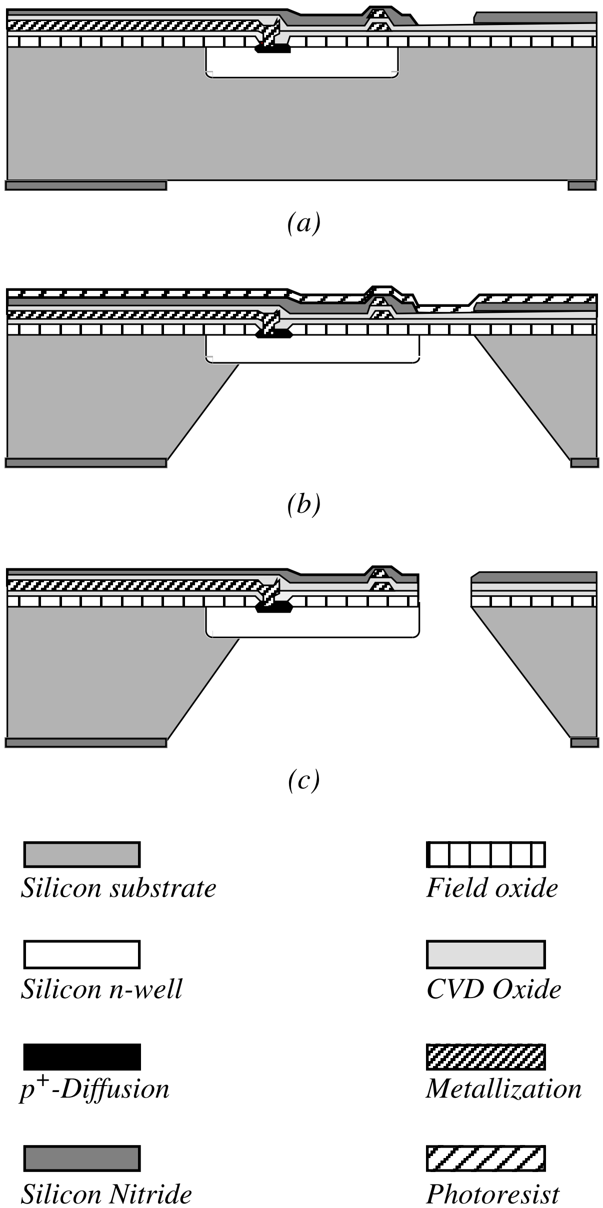

Figure 3: Post-processing sequence of the resonant cantilever, (a) after backside mask patterning, (b) after deposition of protection photoresist and KOH etching process with electrochemical etch-stop, (c) after cantilever release and photoresist removal

process flow is displayed in Fig. 3. In the new design, the n-well has already been shaped as the cantilever and no longer covers the whole membrane area. As shown in Fig. 3 (a), the nitride passivation is opened around the cantilever, so that the dielectric layers comprise the field oxide, contact oxide, and the intermetal oxide. A nitride layer forming the backside mask is patterned to be used as the etch mask. In the next step, anisotropic etching of silicon with KOH is performed. For this purpose, an electrochemical etch-stop technique at the n-well of the CMOS process is combined with an etch-stop at the lowest dielectric layer of the CMOS process, i.e. the field oxide [6]. Due to the nature of the electrochemical etch-stop technique on the n-well, a cantilever-shaped peninsula is created from single crystal silicon. Around the n-well, however, the substrate is completely removed until the field oxide as the lowest dielectric layer is reached. The result of this process step is a cantilever suspended in a dielectric membrane (see Fig. 3 (b)). In the third step, the cantilever is released by opening the 2.4 µm thick dielectric membrane surrounding the cantilever in "Pad Etch" consisting of 13.5 % NH_4F, 31.8 % acetic acid (CH_3COOH), 4.2 % ethyleneglycole ($C_2H_6O_2$), and water. During this step, the top side containing the circuit components is protected with a photoresist while the etchant reaches the oxide layers via the membrane cavity. Since the etchant is selective to silicon, a mask for this process step becomes dispensable. This simplifies the fabrication process. In an improved version, the field oxide was removed during the CMOS process leading to a thinner dielectric membrane and, hence, a reduction of the etch time of 75%.

EXPERIMENTAL RESULTS

To test the feasibility of resonant excitation of cantilever beams, an electromagnetically driven cantilever was connected to a network analyzer and placed in an external static magnetic field directed along the cantilever axis. The magnetic field was provided by a computer-controlled Helmholtz coil, and the dependence of the excitation efficiency on the magnetic field was determined. Since the network analyzer does not contain a current source, but only a voltage source, the resulting current was measured. Fig. 4 shows the amplified output signal from the Wheatstone bridge around the cantilever resonance frequency. As expected, the vibration amplitude was found to depend in a linear fashion on both the excitation current and the magnetic field. For a magnetic field of 100 mT and an ac-current of 1 mA a vibration amplitude of 14.3 nm was achieved. The piezoresistive detection sensitivity using the MOS-transistor Wheatstone bridge biased at 5 V was 48 µV/nm before and 1.52 mV/nm after preamplification. For the same power consumption, the electromagnetic excitation provides vibration amplitudes more than three orders of magnitude

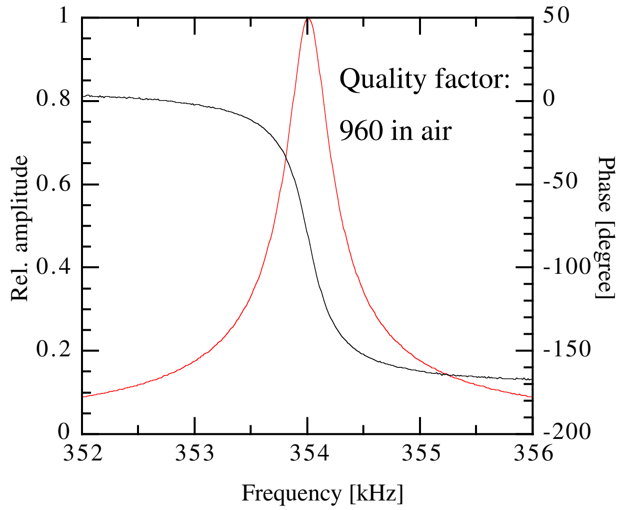

Figure 4: Measured amplitude and phase of the cantilever oscillations around the resonance frequency as a function of the excitation frequency.

higher than is achieved with electrothermal excitation.

Apart from the excitation efficiencies, also the stability of the resonator in an oscillator circuit has been investigated for a constant driving current of 2.5 mA. Fig. 5 shows the short-term stability of the cantilever oscillations as a function of the external magnetic field. For a stable self-oscillation a minimum excitation voltage of 40 mT was necessary. The frequency stability remained at values around 0.03 Hz for higher excitation voltages and could not be further improved, presumably due to limitations of the oscillator circuit. Similar results have been found for the dependence of the frequency stability on the driving current. For stable operation a minimum excitation power of 130 µW was necessary.

CONCLUSIONS

Magnetic actuation of mechanical resonators has been exemplified for a cantilever beam with integrated piezoresistive read-out of mechanical vibrations in view of a lower power consumption. In comparison to diffused resistors, the size of the Wheatstone bridge was drastically reduced. This allows further miniaturization of the cantilever and, hence, higher operation frequencies. Since no counter electrode is needed this excitation scheme offers the possibility to operate resonators in liquids.

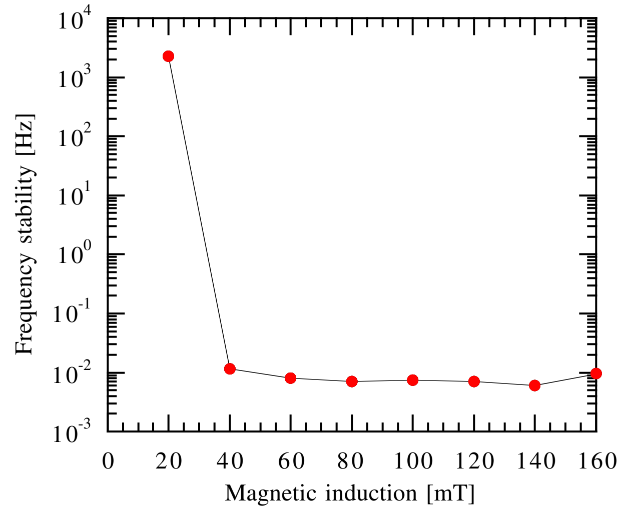

Figure 5: Frequency stability of an electromagnetically excited cantilever beam as a function of the external magnetic field (I = 2.5 mA). The cantilever resonator is operated in a feedback oscillation loop.

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